# Single Atom Resolution Achieved in Graphene

*Individual Carbon Atoms and Defects Imaged*

In a collaboration among scientists in LBNL's Materials Sciences Division and National Center for Electron Microscopy (NCEM), single atom spatial resolution was observed in graphene, a planar, crystalline form of carbon only one atom thick. The study was made possible by the availability of a new-generation electron microscope installed at NCEM this year.

Graphene is a single atomic layer of graphite. Although highly curved graphene derivatives such as carbon nanotubes and fullerenes have been studied extensively, defects and their dynamics in a planar sheet of graphene remain experimentally unexplored. This is due in large part to the fact that planar graphene has only recently become experimentally accessible in an isolated form. Its simple structure has led to its becoming a testing ground for condensed matter physics and numerous experimental and theoretical efforts have been reported recently.

Perfect graphene resembles a linked 2-D lattice of hexagons with carbon atoms at each vertex. In practice, however, graphene is not perfect, and it has been found that its electronic, thermal, and mechanical properties are exceptionally sensitive to the lattice defects. The optimal experimental configuration for defect study in planar graphene is a free-standing membrane, that is, a crystalline foil with a thickness of only 1 carbon atom. This would ideally be probed by microscopy with true single-atom resolution and with a sufficient data acquisition rate to record real-time defect formation and dynamics. Although it would seem that transmission electron microscopy (TEM) would be well suited to this task, the high energy electrons that traditional TEMs use to achieve high spatial resolution would damage the graphene lattice, rendering imaging impossible.

NCEM's new aberration-corrected, monochromated TEAM 0.5 transmission electron microscope operates at 80 kV as compared to 200 kV and higher for older TEMs, but is designed to achieve sub-Ångstrom resolution even at these low electron energies. Using single atomic-layer graphene foils synthesized by Alex Zettl's group, NCEM microscopists led by Christian Kisielowski demonstrated that, in a single exposure, each carbon atom in the field of view could be resolved with no damage to the structure. Moreover, defect structures such as adjoining five- and seven-membered rings ("Stone-Wales defects") could be easily resolved. The motion of these defects was observed in longer exposures providing real-time dynamical information. In another demonstration of the resolution and sensitivity of the new microscope, a series of focused and defocused images was obtained and, after the "exit wave reconstruction" algorithm was applied to process the data, the presence of a single extra single light (C, N, O…) "adatom" was clearly observed.

TEAM 0.5 is the first prototype of a new generation electron microscope that is being developed in a DOE-supported collaborative project led by LBNL. The detection, in this initial study, of single atoms of carbon, showed clearly that this instrument has met project goals and can be used to investigate even light-atom defects such as C-C, C-O or C-N at atomic resolution and to detect single atoms of elements as light as carbon.

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Meyer, J. C.; Kisielowski, C.; Erni, R.; Rossell, M. D.; Crommie, M. F.; Zettl, A. "Direct Imaging of Lattice Atoms and Topological Defects in Graphene Membranes," Nano Lett.; 2008; ASAP Article; DOI: 10.1021/nl801386m

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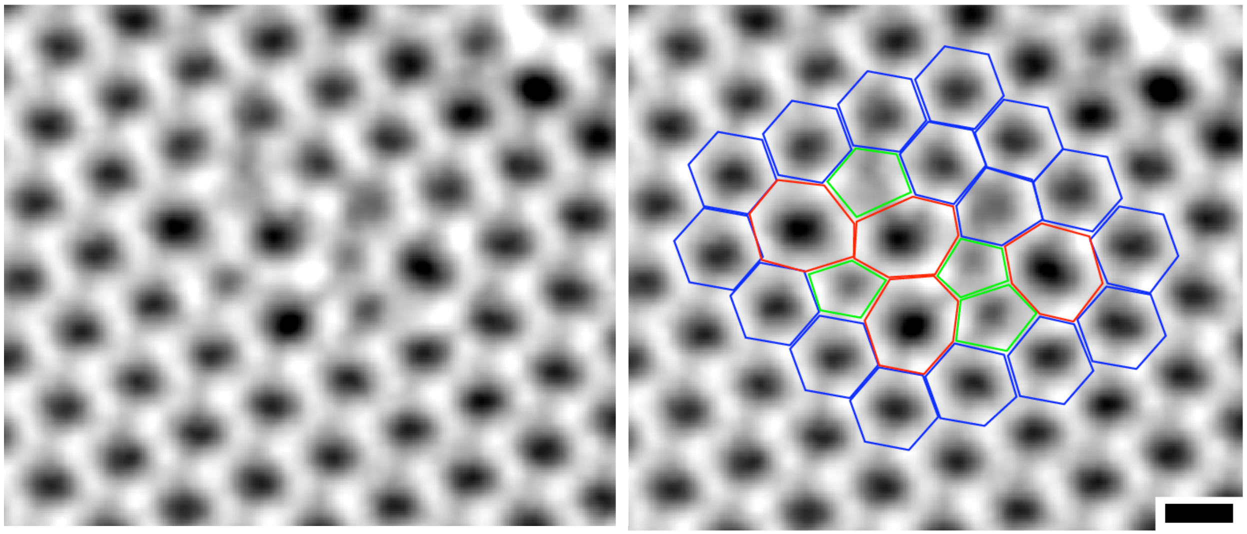
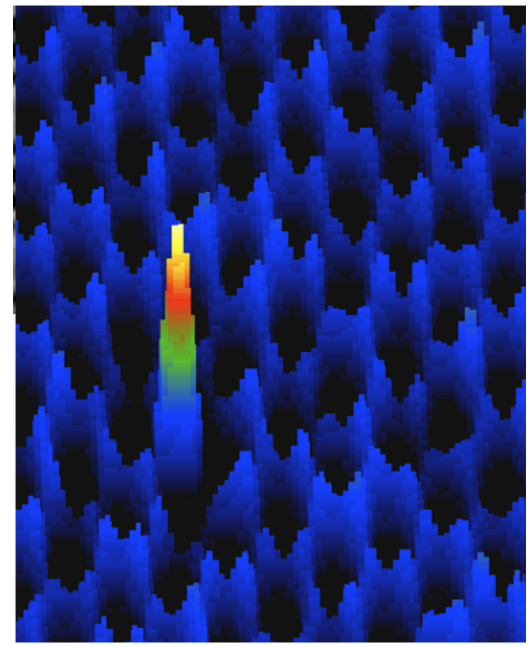


***A new aberration-corrected, monochromated, transmission electron microscope (TEAM 0.5)*** *was used to obtain an image of a single layer of graphene. The electron beam energy was 80 kV, which minimizes sample damage by the beam. The individual carbon atoms appear as bright spots at the vertices of the hexagonal pattern (left). A defect structure consisting of four pentagons (green) and heptagons (red) can be seen in the image on the right. Scale bar is 2 Å.*



***Demonstration of single atom resolution****. "Electron exit wave reconstruction" was used to identify a single additional carbon atom adsorbed on the graphene sheet. (False color showing image intensity on a rainbow scale demonstrates remarkable single -atom contrast).*

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